Synchronization Effect in an Ion Trap Resonator

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Abstract. Using a resonator-like electrostatic ion trap, we demonstrate that, under certain condition, it is possible to keep constant the width of a packet of ions oscillating between two mirrors. We show, using one dimensional calculations, that the effect is the result of Coulomb repulsion which, in a counter-intuitive way, keeps the ions together. Preliminary results of the exploitation of this phenomenon for high precision mass spectrometery are given.

I INTRODUCTION

The dynamics of a cloud of ions stored in an ion trap has been the subject of extensive studies for many years [1]. Using various techniques of cooling, such as laser cooling, it has been shown that transitions from "gas" to "liquid" and finally to "solid" phases can be observed. In this last case, ordering is achieved by the superposition of a strong external focusing force and the Coulomb repulsive force between the stored ions. In general, very low temperatures are needed in order to bring the system to an "organized" state, and usually the experiments can be performed with only a limited set of ions, such as Li^+, Be^+ and Mg^+.

During the last four years, our group (at the Weizmann Institute of Science) has developed and studied a new type of ion trap [2,3], in which fast (keV) ions are stored between two electrostatic mirrors, much like photons in an optical resonator. This ion trap has been used for the study of metastable negative ions [4,5], metastable states in atomic and molecular ions [6,7], and collision induced dissociation, using a beam extraction scheme [8]. In these studies, the trap was used as a "cooling" device, where the excited states produced by the ionization process in the ion source were allowed to decay. Recently [9], we have found that a certain type of ordering can be achieved in such a device with ions at high temperature ($\sim$ 1 eV). In this paper, we present a short overview of this new phenomenon which is related to the dynamics of small bunches of ions oscillating between the trap

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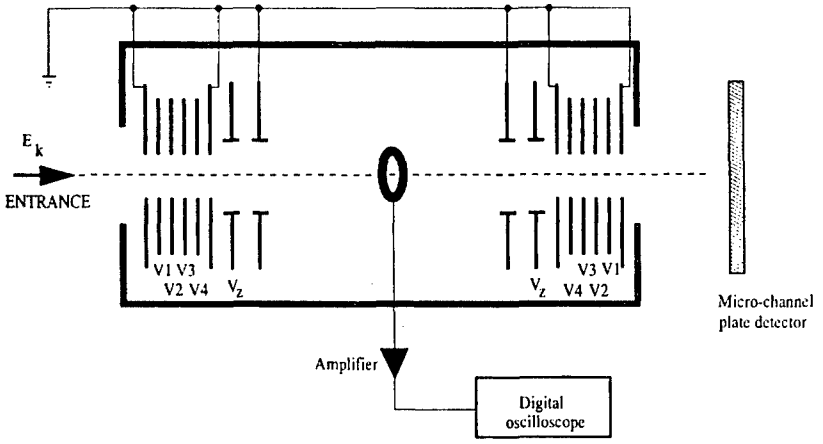

FIGURE 1. Schematic view of the ion beam trap. The bunch is injected through the left hand side of the trap. The central ring is the pick-up electrode. Note that the section between the innermost electrodes of the two mirrors is essentially field free.

mirrors. The effect, which manifests itself as a synchronization of the motion of the ions, leads to the interesting possibility of keeping the size of a packet of ions constant for a practically unlimited time, i.e., eliminating the debunching usually observed for ion bunches.

II EXPERIMENTAL SETUP

A schematic drawing of the electrostatic ion trap is shown in Fig. 1. The mechanical design of the ion trap and its operation have been described previously [2,3]. Briefly, the ion trap consists of two coaxial electrostatic mirrors each composed of a stack of eigth cylindrical electrodes. The configuration of the trap is charaterized by the potentials on five of these electrodes: V_1, V_2, V_3, V_4 and V_z (see Fig. 1), the other three being grounded. Here we investigate a particular set of trap configurations, namely $\{V_1, V_2, V_3, V_4, V_z\} = \{V_1, 4.875\,\mathrm{kV}, 3.25\,\mathrm{kV}, 1.625\,\mathrm{kV}, 4.06\,\mathrm{kV}\}$, where $4.0 < V_1 < 6.0$ kV. These configurations are characterized by a high value of V_z which causes the ions to be strongly focussed inside the mirror region [10].

Injection of an ion bunch into the trap is performed by keeping the electrodes on the entrance side of the trap at ground potential until the bunch enters the trap. The electrodes on the other side are kept at high potentials so that the ions are reflected back toward the entrance. Before the ion bunch returns to the entrance mirror, the potentials of its electrodes are rapidly ($\sim$ 100-200 ns) raised, thus confining the ions between the mirrors. At a residual pressure of 3×10^{-10} Torr, a

typical lifetime of the ions in the trap is $\sim$ 5 s. The trap stability criterion has been demonstrated [2,3,10] to be equivalent to the stability criterion of an optical resonator, namely

$$\frac{L}{4} < f < \infty, \tag{1}$$

where L is the effective distance between the mirrors and f is their focal lengths, assuming that the mirrors are symmetric.

Experiments were performed with ion beams of Ar^+ and Xe^+, at an energy of 4.2 keV, produced in an electron impact ion source. The ions were mass analyzed using two consecutive magnets. The ion currents measured with the help of a Faraday cup located just after the trap were $\sim$ 300 nA for Ar^+, and $\sim$ 100 nA for Xe^+. Ion bunches of 0.2-100 μs were created with an electrostatic chopper.

The evolution of the ion bunch during storage was monitored with the help of a cylindrical pick-up electrode located at the center of the trap. The electrode length was 7 mm, and its diameter was 18 mm. The total capacitance of the pick-up electrode, connectors, and vacuum feedthrough was measured to be $C_p \sim 10$ pF. The pick-up electrode was connected to the gate of a Junction Field Effect Transistor (JFET) whose drain was fed to a charge sensitive amplifier. The amplified signal was recorded with a digital oscilloscope working at a sampling rate of 12.5 MHz, the area A under the signal being proportional to the number of ions N_i in a bunch.

The overall lifetime of the beam is obtained by measuring the rate of neutral particles leaking from the trap, using a microchannel plate (MCP) detector located after the trap. These neutral particles are formed in electron capture collisions between the stored ions and the atoms of the residual gas in the trap.

III RESULTS

A Diffusion

Figure 2(a) shows a typical signal as measured for Ar^+, 200 μs after injection. The pulses are negative due to the polarity of the amplifier, and each pulse represents the passage of about 10^6 ions through the electrode. At this energy, and for this configuration, the oscillation time of the ions was measured to be $\sim$ 3 μs (depending on V_1). The bunch duration, W (see Fig. 2(a)) was initially set to W_0=170 ns, which corresponds to a bunch width of 2.4 cm, which is longer than the length of the pick-up electrode. The development of this ion bunch at later time can be seen in Figs. 2(b-d), showing that debunching occurs on a time scale of $\sim$ 500 μs. In the case shown here, the potential of the last electrode of the trap (see Fig. 1) was set to V_1=5.5 kV. The evolution of the ion bunch was quantified by fitting a Gaussian profile to each peak measured by the pick-up detector, plus a linear background.

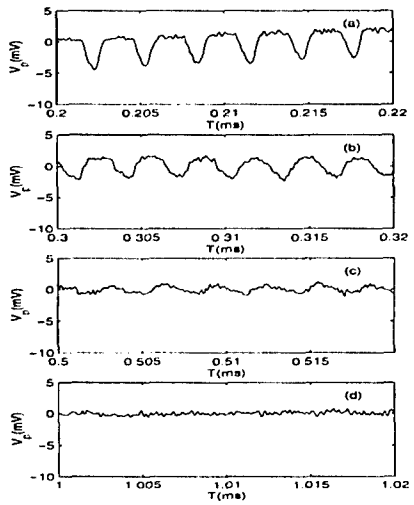

FIGURE 2. The signal observed with the pick-up electrode for an initially 170 ns wide bunch of Ar^+ at 4.2 keV for four different time intervals after injection: (a) 0.20-0.22 ms, (b) 0.30-0.32 ms, (c) 0.50-0.52 ms, (d) 1.0-1.02 ms.

The results of this fit are shown in Fig. 3 where the bunch width W_n is plotted as a function of the number of oscillations n (points). The initially confined bunch of ions is seen to broaden with a characteristic dependence on the number of oscillations. The lifetime of the ions stored in the trap was measured at the same time using the MCP detector and was found to be of the order of few seconds, i.e., much longer than the debunching time. Thus, under these conditions, the trap can be considered to be uniformly filled axially with ions after a storage time of $\sim$ 1 ms. The diffusive behavior illustrated in Fig. 3 was typical for the evolution of bunches for a variety of potential configurations of the trap. In particular, with the configurations under investigation here, this behavior was seen for $V_1 \geq 4.9$ kV. It can be shown [10] that the bunch width evolves as

$$W_n = \sqrt{W_0^2 + n^2 \Delta T^2}, \tag{2}$$

where ΔT is the width of the distribution of oscillation times. This width is due to the initial velocity spread, the different trajectories existing in the trap, and the Coulomb repulsion. The line in Fig. 3 is Eq. 2 with W_0=167 ns and ΔT=5.9 ns.

B Synchronization

Up to now, the behavior of the bunch was shown to follow the time dependence expected from simple arguments. In this part, we will show that a different behavior can be obtained for specific configurations of the trap. Figure 4 shows the evolution

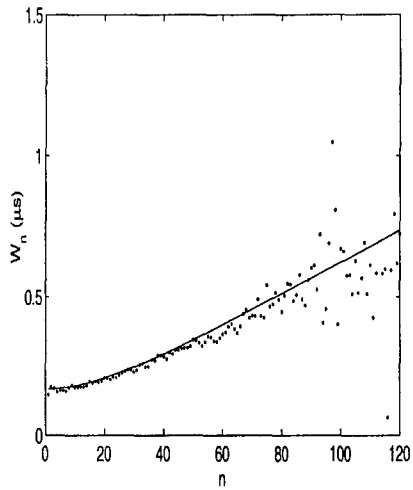

FIGURE 3. Measured bunch width as a function of oscillation number. The line is Eq. 2.

of an ion bunch injected into the trap with an initial width W_0=130 ns. In this specific case, the potential of the first electrode was set to V_1=4.7 kV. In contrast to the diffusive behavior seen in Fig. 2, the width of this ion bunch is conserved over the 90 ms shown in the figure.

More details on the evolution of the bunch can be seen in Figs. 5(a,b) where the bunch width and bunch area are shown as a function of the number of oscillations. After a rapid initial increase, the bunch width (Fig. 5(a)) stabilizes around 120 ns with some fluctuations for the first 5000 oscillations. For the whole time displayed here (and as long as could be measured), the bunch width is found to be constant, behavior very different from that shown in Fig. 3. The bunch area (Fig. 5(b)) shows both increases and decreases during the first 5000 oscillations, indicating that large amounts of ions are both collected and lost from the bunch during this time. Beyond 5000 oscillations, however, the number of ions in the bunch decreases exponentially with time, with a typical lifetime of 270 ms. Clearly, a very strong correlation between the ions is created in this situation, causing the bunch not to spread. This special behavior was observed when the potential of the first electrode was in the range $4.2 < V_1 < 4.9$ kV.

Additional information can be gained when even larger bunches are injected into the trap: In these cases, it was found that immediately after injection, the large bunch would fragment into several smaller bunches. Figure 6 shows the bunch width of the largest stored bunch. The width is seen to first rapidly decrease until it reaches a value of $\sim$ 160 ns. Strong fluctuations are then observed, where the width increases and decreases during about 10^4 oscillations. At this point,

the bunch width stabilizes to a value of 160 ns and stays almost constant. This asymptotic bunch width was found to be a function of the electrode potential configuration (i.e., the value of V_1), and experiments performed with beams of Xe^+ at the same energy showed that the asymptotic bunch width, when measured in units of length, was identical to the the values measured for Ar^+. We have observed motion synchronization for times up to 330 ms (which corresponds to the maximum memory available for our digital oscilloscope) and since no changes in the width were observed on that time scale, one can safely assume that this width is constant for much longer time.

IV DISCUSSION

The origin of the special bunch evolution illustrated in Figs. 5 and 6 lies in the correlation of the ions due to their mutual interaction, which lead to synchronization of their motion [9]. In these cases, the ions in the bunch phase lock their motion due their *repulsive* Coulomb interaction, that effectively causes the bunch width to remain constant. That ions trapped in an electrostatic potential can synchronize their motion due to the *repulsive* Coulomb force between them may at first seem counter-intuitive. To illustrate that such synchronization can indeed occur we

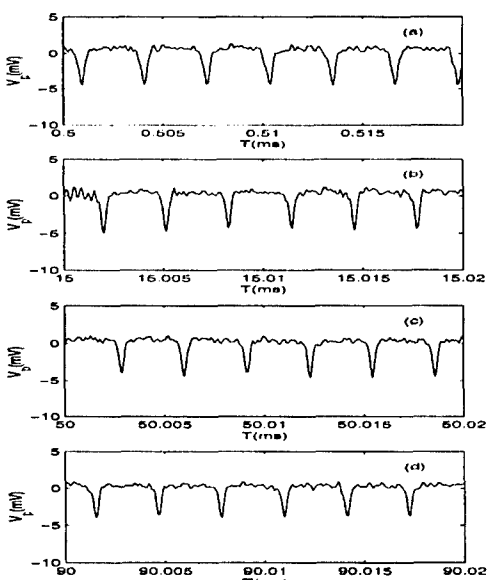

FIGURE 4. The signal observed with the pick-up electrode for an initiually 170 ns wide bunch of Ar^+ at 4.2 keV stored with V_1=4.7 kV for four different time intervals after injection: (a) 0.5-0.52 ms, (b) 15-15.02 ms, (c) 50-50.02 ms, (d) 90.0-90.02 ms

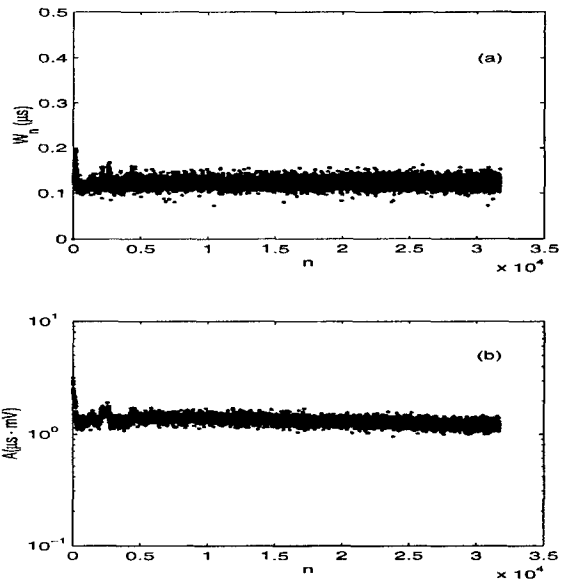

FIGURE 5. Evolution of a bunch of Ar^+ at 4.2 keV initially 170 ns wide, stored with V_1=4.7 kV. (a) The bunch width W_n and (b) the bunch area A.

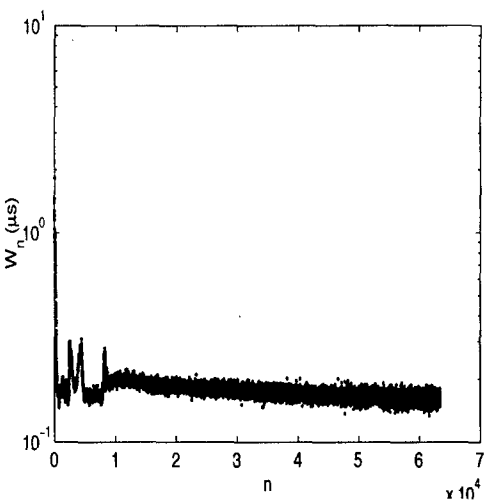

FIGURE 6. Bunch width as a function of the oscillation number for an initially wide bunch.

have numerically simulated the propagation of interacting ions in a flat-bottomed potential well bounded by walls of various slopes.

Clearly, such a model potential is a simplification of the situation existing in the experimental setup described above. However, it will be shown that even under these assumptions, the Coulomb repulsive force can lead to synchronization of the motion of the ions.

For a single ion moving in this potential, the period of oscillation (T) depends only on its energy (E): $T = T(E)$. Hence, for ions with a narrow spread in energy ΔE, the spread in oscillation time ΔT can be expressed as

$$\Delta T = \Delta E \cdot \frac{dT}{dE}. \tag{3}$$

In the simulation, thirty ions moving in the potential described above were followed. In order to allow ions to overtake each other in this one dimensional model, the ion-ion interaction is augmented with a minimum impact parameter ϵ and is given by:

$$F_{ij} = \frac{e^2}{4\pi\varepsilon_0} \cdot \frac{1}{\Delta z_{ij}^2 + \epsilon^2} \tag{4}$$

The initial positions of the ions were chosen randomly according to a normal distribution of mean $\langle z \rangle$=0 and width Δz=0.6 mm, while the initial kinetic energies of the ions were selected from a distribution with mean $\langle E \rangle$=4200 eV and ΔE=0.6 eV. Figure 7 shows the bunch width W_n as a function of the number of oscillations n with (dashed line) and without (solid line) interaction between the particles. Without the interaction, the bunch width increases as expected, with

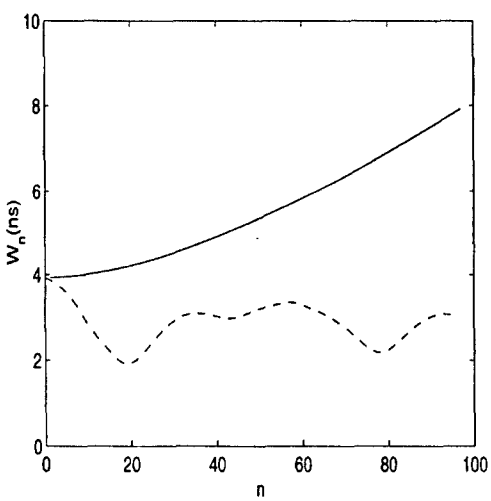

FIGURE 7. Calculated bunch width as a function of the oscillation number: Dashed line: with ion-ion interaction. Solid line: without ion-ion interaction.

a characteristic dependence which is close to the one shown in Fig. 3 and given in Eq. 2. However, when the interaction (Eq. 4) is turned on, the bunch width remains bound, which shows that the ion-ion interaction tends to synchronize the ion motion. It can be shown that the interaction between the ions occurs mainly at the turning points, where the ion density is the highest.

It is important to point out that such behavior is observed over a range of potential slopes, and is not due to a unique configuration known as time focusing, which is often used in Reflectron type electrostatic mirrors [11].

V MASS SPECTROMETRY

Since the trap is purely electrostatic, the oscillation time of an ion depends on its mass-to-charge ratio as

$$T = \frac{1}{f} \propto \sqrt{\frac{M}{q}} \tag{5}$$

where f is the oscillation frequency and M and q are the mass and charge, respectively. Hence, by measuring the oscillation time or frequency the mass-to-charge ratio can be determined. Since, as shown above, it is possible to keep the ions confined in a bunch for a very long time, it might be valuable to try to use such a system for high-precision mass spectrometry, much like the so called Fourier-transform mass spectrometry (FTMS). In the standard version of FTMS [12], the ions are trapped under the influence of magnetic and electric fields, and undergo cyclotron motion. In this case, high resolution is achieved because the ion motion is detected for many cycles, while the packet of ions does not lose its coherence. This is much like the situation we have reached in the present case, when the motion of ions is synchronized. However, if different masses are injected at the same time into the trap, would the "synchronization" effect be too strong, "capturing" all the ions (with different masses) in a single bunch?

To answer this question, we have performed a preliminary experiment in which two different isotopes of xenon ($^{131}Xe^+$ and $^{132}Xe^+$) with the same kinetic energy were injected at the same time into the ion trap. Figure 8 shows the fast Fourier transform (FFT) of the measured spectrum, after 200 ms of storage. The resolution is greatly improved over the non-synchronized cases (not shown) and the two isotopes are well separated, with a frequency difference which is in good agreement with the expected value. The resolution obtained in this case is $\Delta m/m = 2\Delta f/f = 6 \cdot 10^{-5}$, and this resolution improves with longer measurement times. More work needs to be done on this subject, but we have already observed additional effects such as frequency shifts for specific values of V_1, indicating that the interaction between the bunches can be important as well.

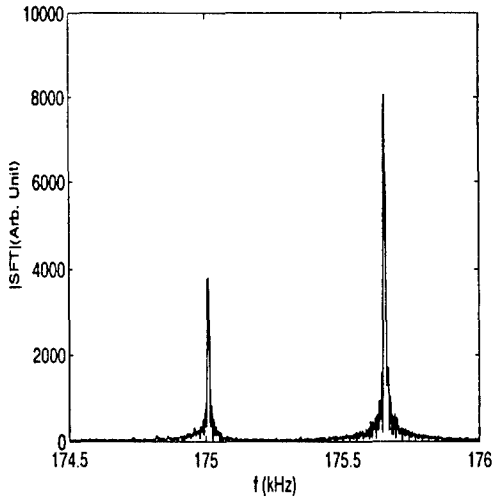

FIGURE 8. Fast Fourier transform of the pick-up signal for two isotopes of Xe^+ in the synchronized mode ($^{131}Xe^+$ is the right peak and $^{132}Xe^+$ is the left peak.

VI CONCLUSIONS

Using an electrostatic ion trap which allows for the trapping of fast ion beams, we have demonstrated that it is possible to keep the length of a bunch of ions constant, for a time which is much longer than expected. The effect shows up for specific values of the potential profile in the mirror regions. The asymptotic bunch width was found to be a characteristic of the ion trap geometry and the potential configuration. We have shown, using a simple one dimensional model, that such an effect is due to the Coulomb interaction between the ions. Preliminary results related to the use of such a system for high resolution mass spectrometry have also been obtained.

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